Thermal and Pressure Characterization of a Wind Tunnel Force Balance using the Single Vector System (SVS)

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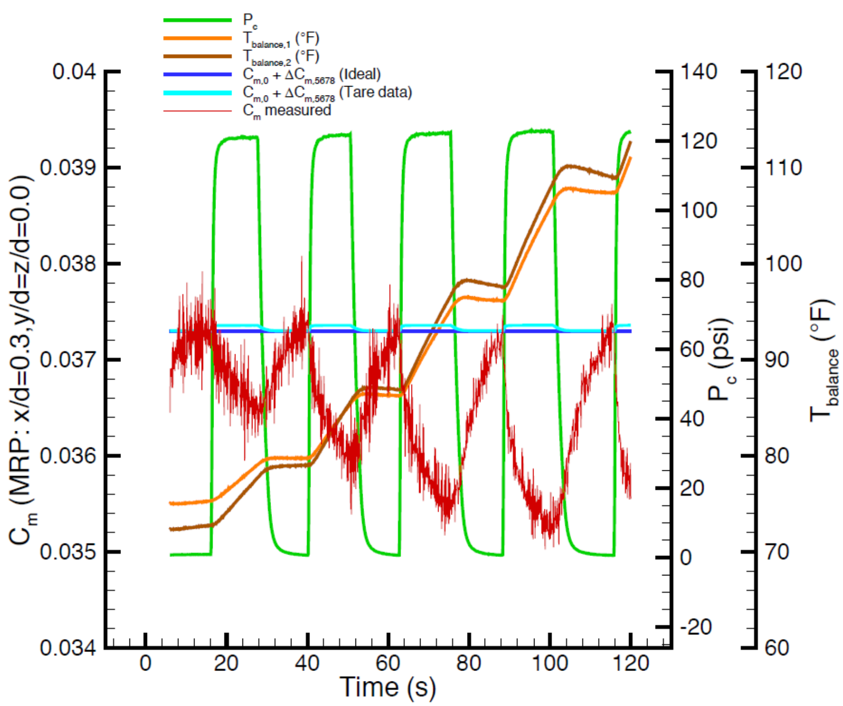
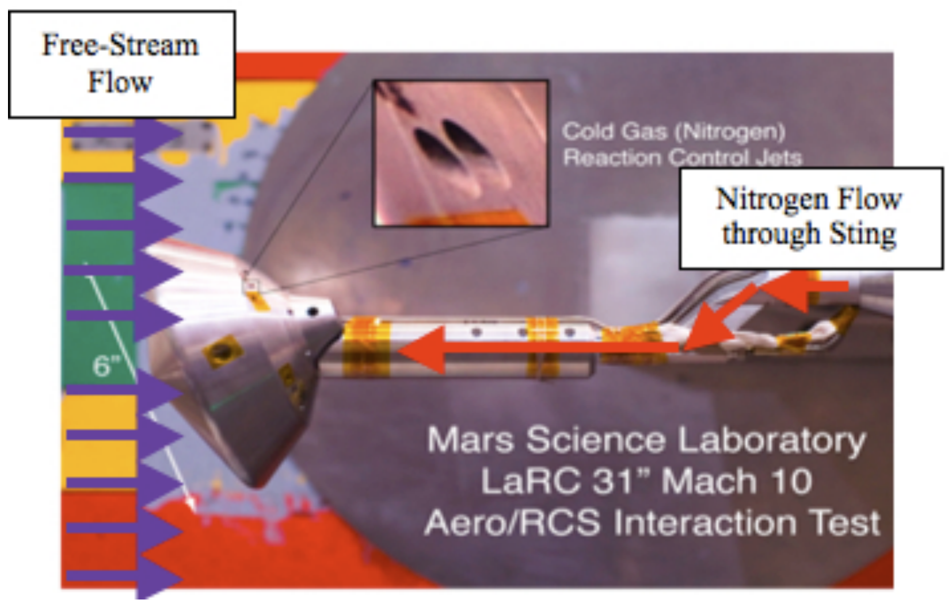
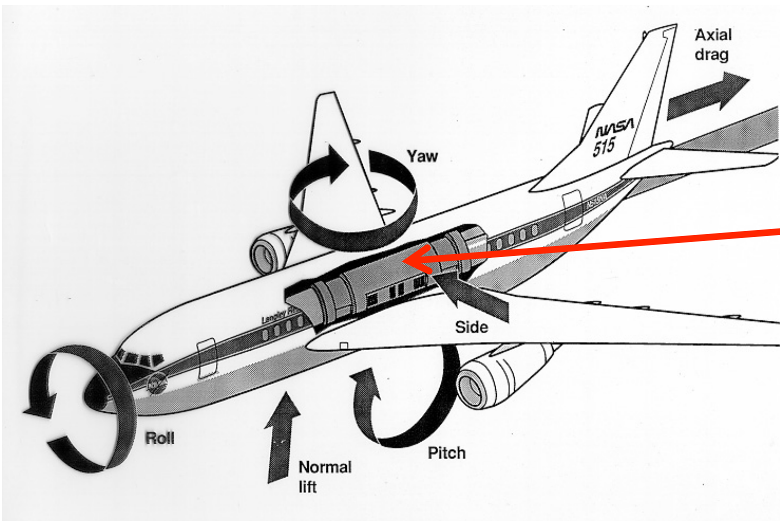
Motivation

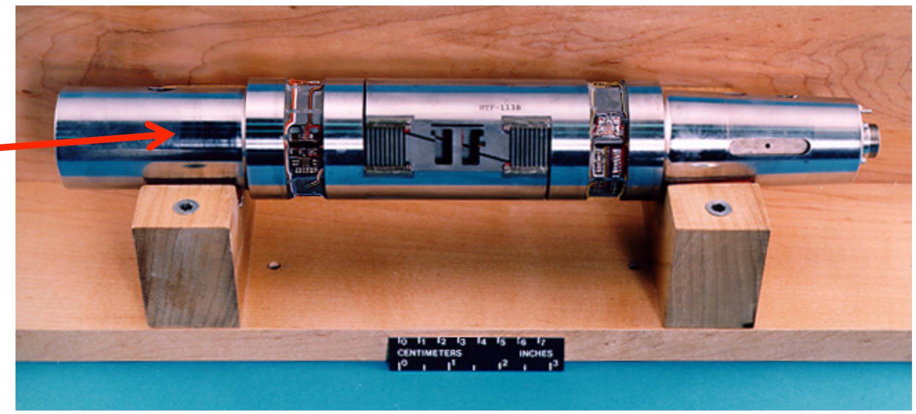
- Previous testing at the NASA LaRC 31-Inch Mach 10 facility with the Mars Science Laboratory (MSL) aeroshell revealed several thermal related issues during tests.
- Primary issue involved temperature drift of the force balance over the duration of each blow-down run.
- Worst-case temperature drift observed during RCS pressure cycle runs (cycling reaction control jets on-off) was ~ 40°F over 120 second run time.
- MSL research team proposed the following problem statement:
  - Pursue having balance team at NASA LaRC design method for characterizing the outputs of the strain-gages subject to various forces, moments, pressures, and temperatures





What is a Force Balance?

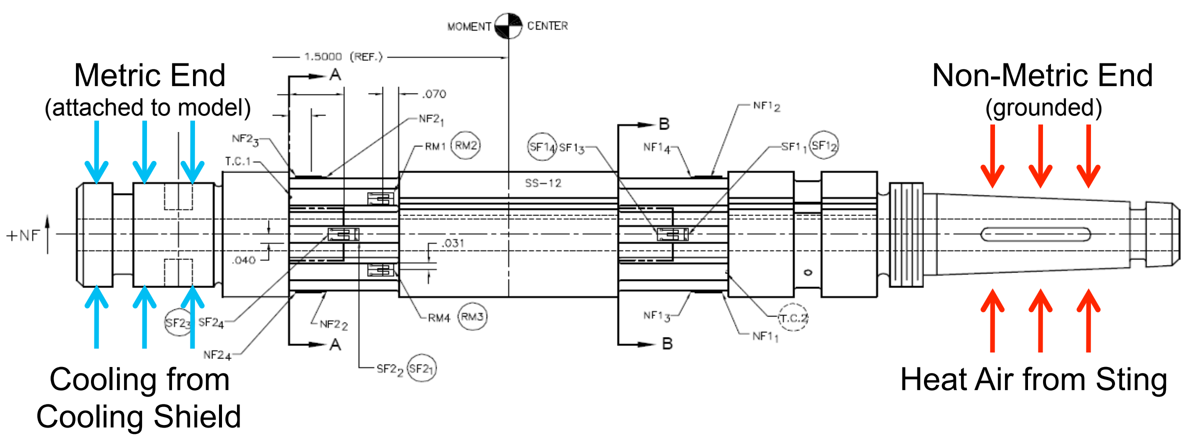




- Force Balances are transducers used to measure the 6DOF aerodynamic loads encountered by a wind tunnel model during a wind tunnel test
- Balances are complex structural spring elements composed of flexural elements – only structural component between model (metric end) and sting (non-metric end)
- Flexures are instrumented with foil resistive strain gages that output an electrical signal which is proportional to the strain level induced onto the flexural elements
- Balance structure and instrumentation designed to be sensitive to only single component applied loads/moments, but imperfections (in machining/instrumentation) require us to characterize interactions

SS-12 Force Balance

- SS-12 is a single-piece, 5-component, water-cooled, flow-thru force balance (no Axial Force)
- Balance has a concentric hole down its center, allowing flow of gas thru balance and out to attached model on metric end
- Normal force and side force components re-gauged from direct read to a force type balance configuration (N1, N2, S1, S2, RM)
  - N1/N2, S1/S2 bridges at a single axial station along balance
  - Single station bridging of strain gages aids in reducing sensitivity of measurement bridges to thermal effects
- Balance design features an active cooling shield that covers balance during use, and actively cycles water around balance (typical for balances used in supersonic/hypersonic testing regimes)



Component	Design Load
NF	100 lbs
AF	n/a
PM	150 in-lbs
RM	32 in-lbs
YM	40 in-lbs
SF	30 lbs

Pre-Experimental Planning

Collaboration amongst all colleagues to clearly establish objectives and factor level settings.

- A clear statement of the goals/objectives of an experiment is critical (Answer the <u>right question(s)</u>.)
  - <u>Objective:</u>
    1. Characterize the outputs of the strain-gages subject to various forces, moments, pressures, and temperatures (develop continuous functions for each measurement component)
- Selection of the factors and measured responses
  - Aerodynamicists, Force Measurement Engineers and Statistical design experts collaborated to determine optimal solution to meet objectives
  - Design, Held-Constant, Uncontrolled Factors
  - Design Factor ranges:
    - Forces and Moments → full-scale range balance design loads (which match the expected test loads)
    - Pressure and Temperature → range over expected operating conditions during wind-tunnel test
  - Design Factor Levels: support experimental objectives

<u>Design Factors:</u>

Factor Label	Design Factor (units)	Range
A	Normal Force *(lbs)*	-100 to +100
B	Pitching Moment *(in-lbs)*	-150 to +150
C	Rolling Moment *(in-lbs)*	-32 to +32
D	Yawing Moment *(in-lbs)*	-40 to +40
E	Side Force *(lbs)*	-30 to +30
F	Average Balance Temperature*(°F)*	70 to 120
G	Balance Cavity Pressure *(psia)*	14.7 to 400

<u>Measured Responses:</u>

Response	Response Type (units)
1	Normal Force Bridge Output *($\mu V/V$)*
2	Pitching Moment Bridge Output *($\mu V/V$)*
3	Rolling Moment Bridge Output *($\mu V/V$)*
4	Yawing Moment Bridge Output *($\mu V/V$)*
5	Side Force Bridge Output *($\mu V/V$)*

Experimental Design

- Fundamentals of Statistical Design of Experiments
  - Randomization: defends against systematic errors (i.e. hysteresis) in an experiment.
  - Replication: provides information on the pure experimental error in the response, which sets the lower bound for uncertainty.
  - Blocking: limits the effects of any nuisance (controlled or uncontrolled) factors in an experiment.
- Postulated Mathematical Model: based on Taylor series expansion
- Balances are highly dimensional instruments, requiring response surface methods to properly characterize performance over design-space
- Two Experimental Designs Generated & Executed
  - Crossed Design & IV Optimal Design (both designs are Split-Plot (SP) designs)
  - Forces/Moment load schedules based off Central Composite Design (CCD)

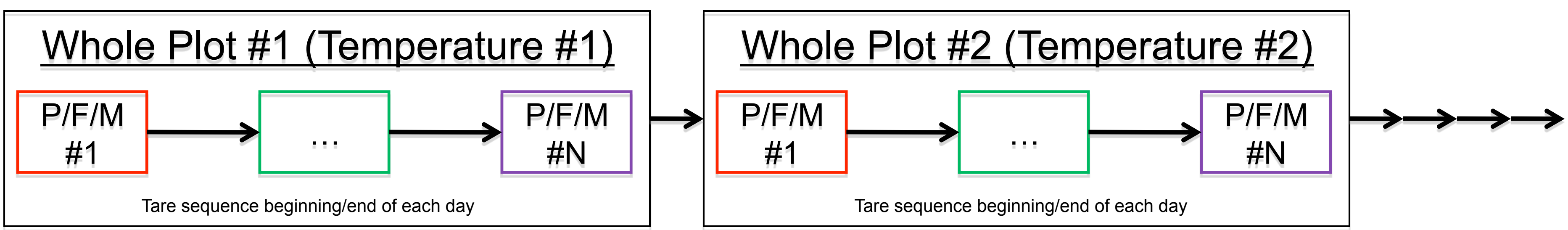
$$y = \beta_0 + \sum_{i=1}^{7} \beta_i x_i + \sum_{i=2}^{7} \beta_{ii} x_i^2 + \sum_{i=1}^{7} \sum_{j=i+1}^{7} \beta_{ij} x_i x_j$$

$$x_1 = \text{Temperature} \quad x_2 = \text{Pressure} \quad x_3 = \text{NF} \quad x_4 = \text{PM} \quad x_5 = \text{RM}$$

$$x_6 = \text{YM} \quad x_7 = \text{SF}$$

Calibration Execution *(Crossed Design)*

- Presence of hard-to-change factors in an experiment can make a completely randomized experimental design impractical to implement.
  – Temperature is often an expensive/time-consuming factor to change
- Split-Plot designs are a technique to deal with experiments with hard-to-change factors
  – Restrict randomization for hard-to-change factors
  – Concept developed from agricultural experiments
- Temperature is set and held constant while pressure, forces, and moments combinations are varied randomly for each point within each whole plot
  - Because of time required to complete, design is blocked by day. Once temperature is set, it does not change for the rest of that day.
- Calibration occurred over the course of 8 days
  – 2 days for standard calibration
  – 6 days for pressure/temperature calibration



Development of the Experimental Design 1

(Crossed Design)

5-Component SVS Design:

Factorial Design Points

NF	PM	RM	YM	SF
-48	-72	± 15	-19	-13
-48	-72	± 15	19	13
-48	72	± 15	-19	13
-48	72	± 15	19	-13
48	-72	± 15	19	-13
48	-72	± 15	-19	13
48	72	± 15	-19	-13
48	72	± 15	19	13
0	0	0	0	0

Axial Design Points

NF	PM	RM	YM	SF
± 100	0	0	0	0
± 100	± 150	0	0	0
± 100	0	0	0	± 30
± 100	0	± 32	0	0
0	0	0	± 40	± 30
0	0	0	0	± 30
0	0	0	0	0

Factorial Points:	16
Axial Points:	20
Center Points:	6
Total:	***42***

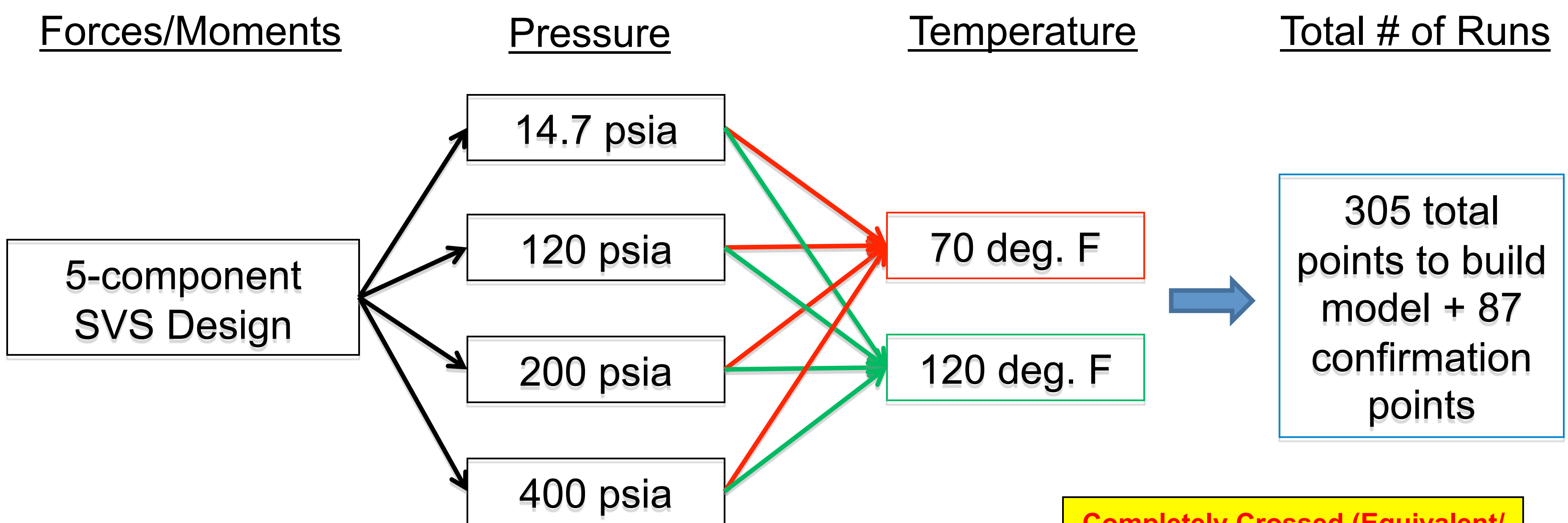
Development of the Experimental Design I

(Crossed Design)

Mathematical Model Assumptions:

- First-order effect of temperature on responses (req. 2 unique levels)
  - Assumption based on experience, historical data
- Second-order effect of pressure, forces, and moments on responses (req. 3 unique levels)

Experimental Design Development:



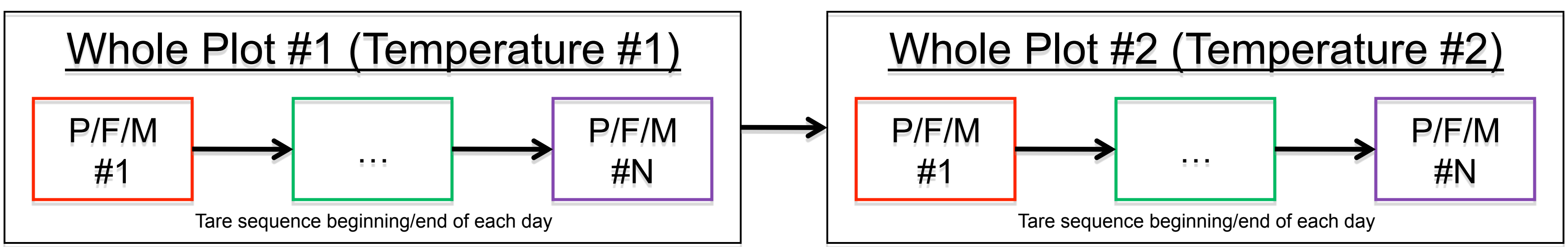
Completely Crossed (Equivalent/ Balanced Design)

Development of the Experimental Design II & Execution *(Optimal Design)*

<u>Mathematical Model Assumptions:</u>

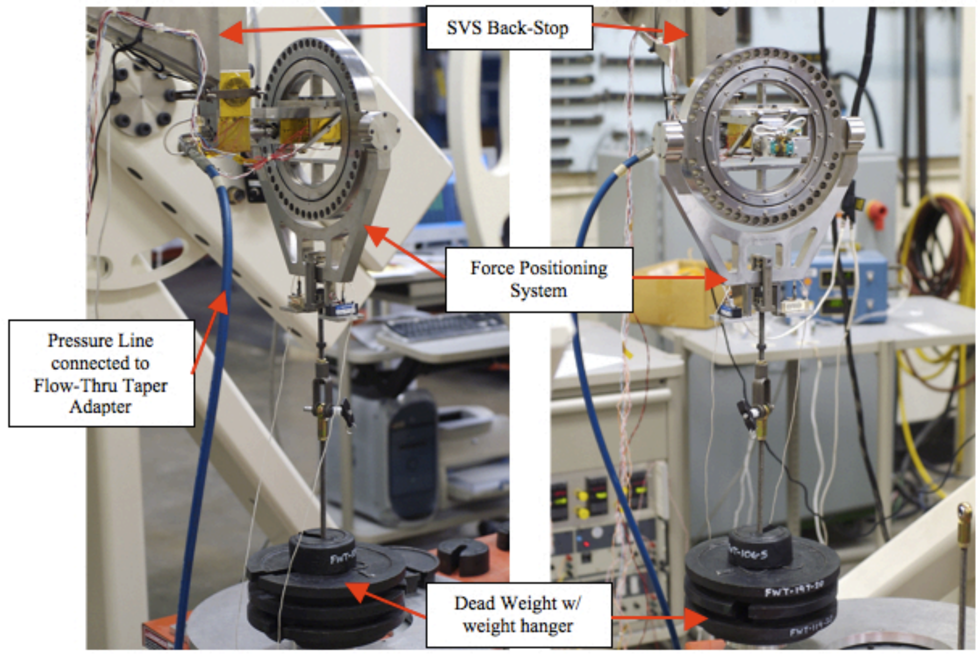
- Same as Crossed Design

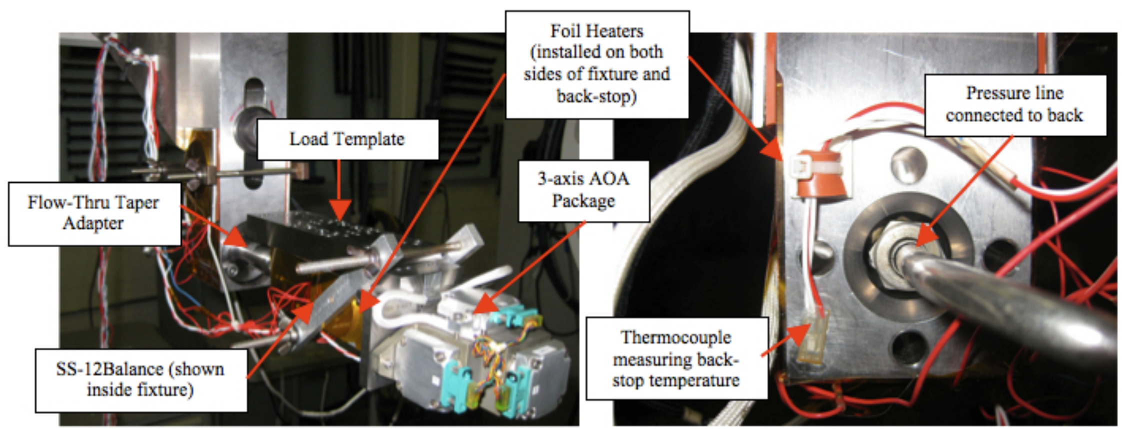
- Crossed experimental design points used as a candidate list within DE to generate an optimal design
  - Completely Crossed design contained all possible combinations possible using SVS, based on common CCD design
  - IV Optimal Design used as it provides a lower prediction variance across the design space (desirable for instances when prediction capability is critical)
  - 44 point design generated & executed (plus 42 point room temp design – needed to provide sufficient DOF in order to compute T main effect term)
- Design properties (leverage, VIF's, SE) inspected to ensure good selection of design points



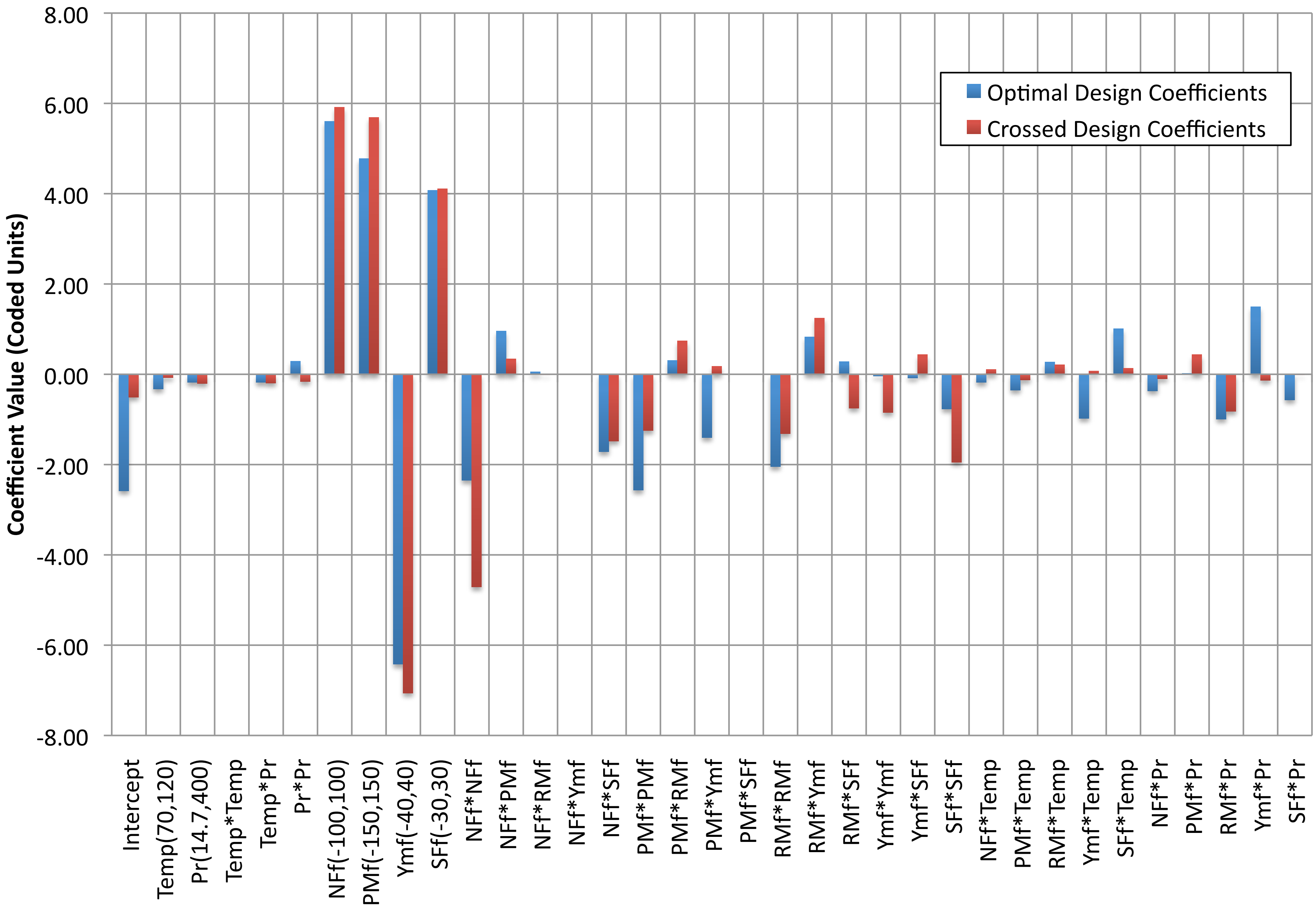
Calibration Setup

- Single Vector System (SVS) used during calibration to orient balance
- Heater system configured with foil heaters on balance calibration block and SVS back-stop to elevate steady balance temperature to desired settings.
  - Temperatures actively controlled to within 1-2 °F of desired set point
- Static pressure applied to internal balance cavity via pressure fitting in rear of stump adapter.
  - Cap plate on forward most end of balance calibration block sealed off system, allowing application of static pressure to balance
  - Nitrogen k-bottle used for air source

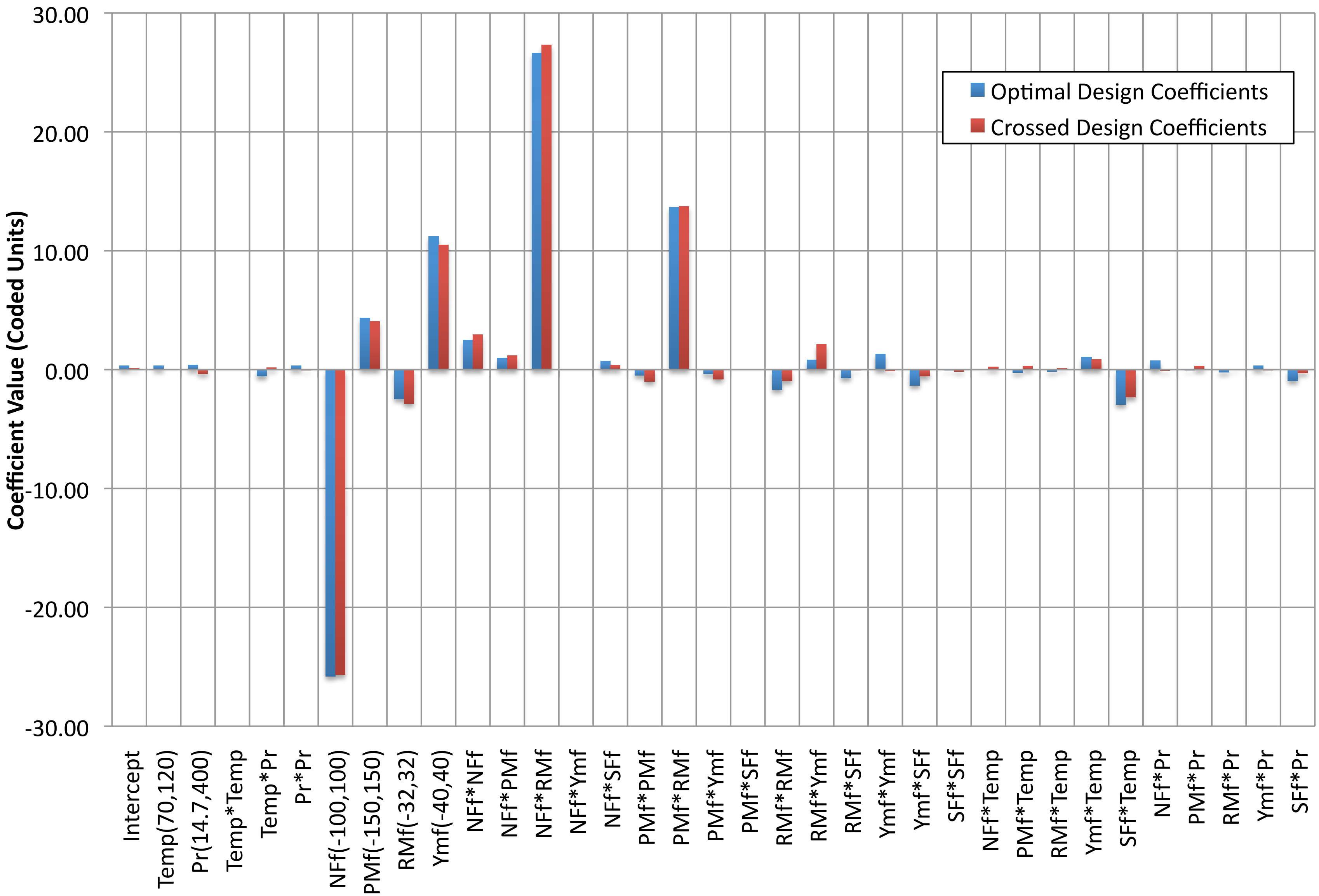




Results: Model Comparison
(RM Response)



Results: Model Comparison
(SF Response)



Results: Model Summary

- No model reduction employed
- Tare data collected during calibration used to reduce data, in order to get total applied loads
- Data from both Completely Crossed & Optimal designs analyzed using REML in JMP
- Each design clearly shows improved prediction accuracy when Pressure/Temperature model coefficients included
- Small differences in prediction accuracy estimates exist between crossed and optimal designs

	2sigma (%FSE)				
	NF	**PM**	**RM**	**YM**	**SF**
optimal + room temp data, w/ P and T	0.1104	0.0918	0.5715	0.1579	0.2054
optimal + room temp data, w/o P and T	0.1497	0.1186	0.5404	0.1857	0.2503

	2sigma (%FSE)				
	NF	**PM**	**RM**	**YM**	**SF**
crossed design, w/ P and T terms	0.0849	0.0699	0.4637	0.1185	0.1628
crossed design, w/o P and T terms	0.1218	0.1077	0.4776	0.1645	0.2095

Conclusions

- An engineering problem was presented to the team. A methodical approach was developed to solve this problem, which combined efforts from both engineering and statistical fields of expertise.
- Demonstrated a method to characterize the force balance in the wind tunnel environment, including temperature and pressure, thereby improving aerodynamic research data quality
  - Data from calibration and MSL test data reveals significant improvement (multiple sources contribute to increased data improvement)
- Calibration data reveals both designs result in very similar mathematical models, with very similar residual/accuracy estimates
- Appropriate metrics were determined to evaluate the robustness of the experimental design, developed for this specific calibration.
- With appropriate planning and coordination, the methods described from this investigation can be applied to any calibration to yield a powerful mathematical model that characterizes the performance of the system under consideration.
- Resulting mathematical models (algorithms) generated were transferred to the wind-tunnel test team, and the on-board compensation techniques were applied real time during the test.

Contacts and References

- **Contacts for more information:**

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  Thomas Johnson (thomas.h.johnson@nasa.gov)

  Peter Parker (peter.a.parker@nasa.gov)

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